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Published in:
I E E E Photonics Technology Letters

Link to article, DOI:
10.1109/68.998704

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

Heterodyne Technique for Measuring the Amplitude and Phase Transfer Functions of an Optical Modulator

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Abstract—**In this letter, we propose a technique based on heterodyne detection for accurately and simultaneously measuring the amplitude and phase transfer functions of an optical modulator. The technique is used to characterize an InGaAsP multiple quantum-well electroabsorption modulator. From the measurements we derive the small-signal α-parameter and the time-dependent chirp for different operation conditions.**

Index Terms—**Chirp, electroabsorption, modulation, optical interferometry, optoelectronic devices, phase measurement, phase modulation, semiconductor devices.**

THE USE OF external modulators such as Mach–Zehnder interferometers (MZIs) or electroabsorption modulators (EAMs) has proven advantageous for the reduction of the transmitter pulse chirp, compared to directly modulated semiconductor lasers [1], [2]. Even precompensation of the fiber dispersion is possible with these modulators and the monolithic integration of a laser and an EAM makes the EAM a very promising device.

The chirp imposed on the modulated signal, being generated by a laser or an external modulator, is due to the refractive index modulation accompanying the intensity modulation. Temporal phase modulation, induced by the change in refractive index, generates additional frequency components to the pulse. In an external modulator, the transmission is controlled by the applied bias. The phase as a functions of the bias voltage characterizes completely the chirp-properties of the modulator when the time dependence of the voltage is known. The α-parameter can then be derived from the slopes of the phase and transmission curves versus voltage, providing the bias dependent α-parameter.

A number of techniques have previously been used to measure the α-parameter in electroabsorption modulators. Saunders [3] used a MZI to convert the frequency modulation into a measurable intensity modulation which was used to calculate an average α-parameter. Devaux [2] used a network analyzer and a transmission line to measure mainmode and sidemode beatings for a small-signal modulation, giving the α-parameter for the applied voltage offset. By measuring the intensity transfer function in a second experiment, Devaux calculated the phase change in an EAM for a few reverse bias points [4].

Manuscript received October 29, 2001; revised December 17, 2001. This work was supported by the Danish Research Council through the SCOOP program.

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Publisher Item Identifier S 1041-1135(02)03224-X.

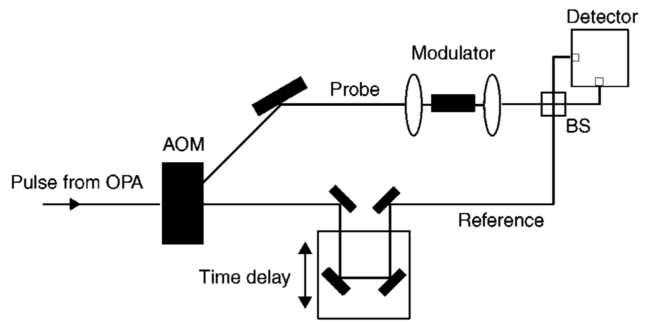

Fig. 1. Schematic of the setup. The device to be characterized is inserted in the one arm of a free space MZI. The 39-MHz frequency shifted pulse propagates through the modulator and is spatially and temporally overlapped with the unshifted reference pulse in the beam splitter (BS). The balanced detectors measures the beating signal.

In this letter, we demonstrate a technique for simultaneous measurement of the amplitude and phase transfer function of an EAM as function of a continuous voltage swing. The α-parameter is calculated directly as function of the applied bias, and the chirp profile for all operation points can be calculated. The advantages of this technique over the previously mentioned are real-time full amplitude and phase transfer function measurement and simple α-parameter calculation.

Our amplitude and phase sensitive technique is based on a heterodyne detection scheme, presented in [5]. Fig. 1 illustrates the principle where the component is inserted in one arm of a free space MZI. A small fraction of a 200-fs optical pulse from an optical parametric amplifier is diffracted and frequency shifted using an acoustooptic modulator (AOM). The diffracted pulse is coupled into and out of the EAM using high numerical aperature (NA) aspheric microscope lenses with an estimated coupling loss of 5 dB. After propagation through the EAM waveguide, the pulse is superposed with the nondiffracted reference beam in a beam splitter. A time delay is included in the reference beam path to overlap the probe and reference pulses temporally. A balanced detector measures the two quadratures from the interferometer. The 39-MHz frequency shift (Δf) and the following superposition with the reference beam gives a beating signal with mode spacing of 295 kHz, equal to the repetition rate (R) of the optical source. The current from the balanced detector can for each beating mode (n) be written as

$$i_n(t) = \frac{2e\eta}{h\nu}\sqrt{2P_s(V)P_r} \cos(2\pi(\Delta f - nR)t - \phi_r + \phi_s(V)) \quad (1)$$

where η is the detector efficiency, ν is the carrier frequency and P_s and P_r are the probe and reference powers, respectively. The optical reference and probe phases are ϕ_r and ϕ_s, respectively. The $P_s(V)$ and $\phi_s(V)$ indicate the dependencies of probe power and phase on the voltage applied to the EAM. The current from the detector is amplified in a preamplifier before it is measured with a lock-in amplifier.

The reference signal for the lock-in amplifier is generated by down mixing the 39 MHz sinusoidal electrical signal with a high harmonic $(n)$of the laser repetition rate. An appropriate filtering of this signal ensures that only the lowest harmonic is detected by the lock-in. By fine tuning the repetition rate of the system, a mode beating below the 100 kHz bandwidth of the dual phase lock-in amplifier can be achieved.

The signal measured by the lock-in is proportional to the probe and reference field amplitudes, and the signal phase compared to the lock-in reference represents the optical phase delay. The probe pulse traveling through the waveguide has a pulse energy of <500 fJ, which was measured to be in the small signal regime of the EAM. The reference beam has pulses with ~100 pJ of energy. The noise of the system is dominated by the laser intensity noise inherent to the Coherent OPA laser system. The 10-nm broad spectrum of the 200-fs pulse introduces a spectral averaging of the amplitude and phase response function. However, spectral narrowing by pulse-shaping can be used to increase the spectral resolution.

To change the reverse bias over the EAM, a function generator is used. The bias is modulated using a saw-tooth shape with a 0 to −5 V swing. The modulation frequency is 55 Hz. The in-phase (X) and out-of-phase (Y) components from the lock-in amplifier are recorded on an oscilloscope scope, triggered from the function generator. Averaging on the oscilloscope is necessary to reduce the noise. From the X and Y components the relative amplitude transmission (T) and phase (ϕ) are calculated, $T = \sqrt{X^2 + Y^2}$ and $\phi = \arctan(Y/X)$, respectively.

The investigated device is an InGaAsP electroabsorption modulator with ten quantum wells. The length is 200 μm. The component had an insertion loss of ≈12 dB at 1550 nm.

The measured intensity and phase transfer functions are shown in Fig. 2. The measurement was performed with TE polarized light at 1550 nm. The intensity transmission (T^2) shows, as expected, a reduction of the transmission as the reverse bias is increased. For a voltage sweep from 0 to −5 V an extinction of 15 dB was obtained. The phase is increased for increasing reverse bias until −3.3 V, where the phase starts to decrease again. The observed maximum and change of sign of the first derivative of the phase indicates a favorable working point for low chirp. The α-parameter can, in our case of voltage modulation, be written as follows:

$$\alpha = \frac{\Delta(\mathrm{Re}(\chi))}{\Delta(\mathrm{Im}(\chi))} = \frac{\frac{d(\mathrm{Re}(\chi))}{dV}}{\frac{d(\mathrm{Im}(\chi))}{dV}} \tag{2}$$

where χ is the material susceptibility. The α-parameter is calculated using the standard definitions of refractive index and gain,

$$\alpha(V) = -\frac{\frac{2d\phi}{dV}}{\frac{d(\ln(I))}{dV}} \tag{3}$$

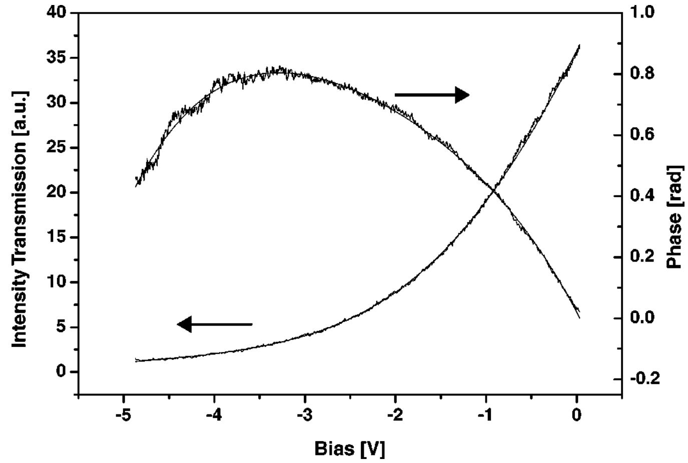

Fig. 2. Measured intensity transmission and phase as a function of the applied reverse bias. Polynomial fits of the data are also shown.

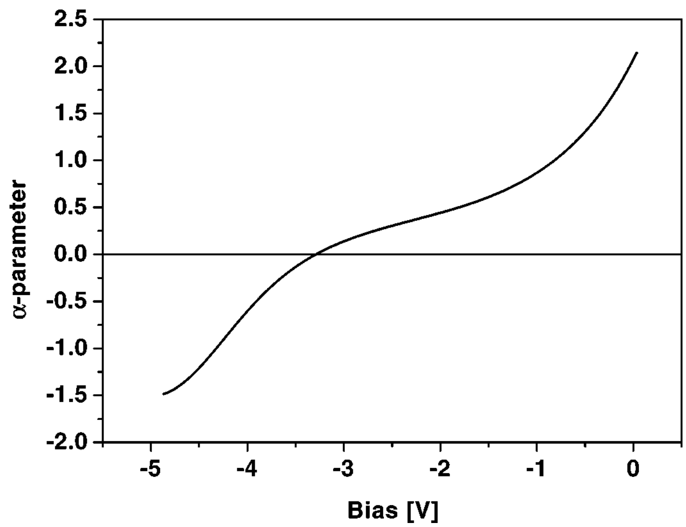

Fig. 3. The α-parameter calculated using (3) with the polynomial fit of the intensity and phase transfer functions shown in Fig. 2.

where ϕ is the phase, defined as increasing for increasing refractive index. I is the relative intensity transmission.

Fig. 3 shows the α-parameter derived from the measurements in Fig. 2 using polynomial fits of the measured amplitude and phase. The magnitude and bias dependence of the α-parameter is in good agreement with previous measurements and calculations on similar structures [4], [6], [7].

To show the effect of the intensity and phase modulation at high bit rate, we calculate the response of the device to a 10-Gb/s nonreturn-to-zero (NRZ) electrical modulation of the bias voltage. The 10-Gb/s NRZ electrical signal used for the calculation was a super Gaussian fit to a measured 10-Gb/s electrical signal from a test set. The response is calculated from the fits of the intensity and the phase transfer functions. Fig. 4 shows the case of a $3V_{pp}$, modulation of the voltage around −1.5 V. The extinction ratio is 9.2 dB and the maximum frequency excursion is ±3 GHz, corresponding to ±0.02 nm. The pulse is chirped with a blue-shifted leading edge and a red-shifted trailing edge, which is often referred to as positive chirp. If instead the offset voltage is set to −3.3 V where the α-parameter is zero, a substantial reduction of the chirp is possible. This

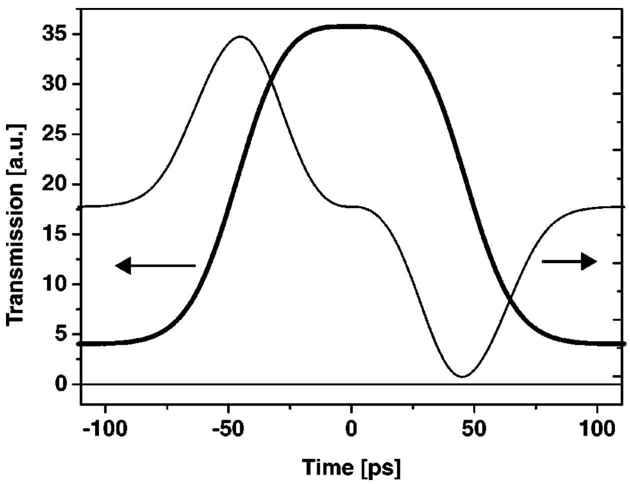

Fig. 4. Calculated response of the EAM for a 10-Gb/s NRZ modulation using a $3V_{pp}$ modulation and -1.5-V offset.

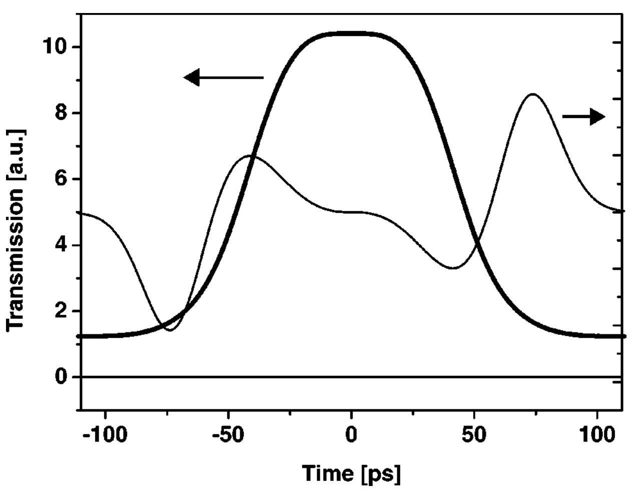

Fig. 5. Calculated response of the EAM for a 10-Gb/s NRZ modulation using a $3V_{pp}$ modulation and -3.3 V offset.

is shown in Fig. 5. The extinction ratio is 9.2 dB and the insertion loss is increased by 5.5 dB. The shape of the chirp is different in this case. Initially, there is a red shift of 2 GHz explained by the negative α-parameter for voltages below -3.3 V. In the main part of the pulse, there is a ± 1 GHz frequency excursion, corresponding to a reduction of a factor of three compared to the case of $V_{pp} = 1.5$ V. In the trailing part of the pulse, there is a blue shift of 2 GHz, again due to the negative α-parameter in this voltage range. Since the ± 2 GHz of chirp is in the low intensity parts of the pulse it is not expected to contribute significantly to the pulse broadening. Initially, these frequency components will even compress the pulse due to the fiber dispersion. For propagation in single mode fiber at 1550 nm the operation point of -3.3 V is advantageous compared to -1.5 V, due to its reduced chirp. Corresponding results for a different modulation frequency is represented by a simple scaling of the time and frequency axes.

Finally, the authors propose a simpler experimental setup. Using instead a radio frequency lock-in amplifier or a radio receiver, detection directly at 39 MHz is possible. Thereby, the pulsed operation of the probe and reference is no longer necessary and a continuous-wave laser source can be used. The increased duty cycle will increase the signal to noise ratio and the modulation frequency of the EAM can be increase into the kilohertz regime.

In summary, we have demonstrated the use of a heterodyne detection scheme for the simultaneous measurement of the amplitude and phase transfer functions of an optical modulator. The transfer curves of an electroabsorption modulator are measured and the corresponding small-signal α-parameter has also been derived; it decreases from 2.1 at 0 V to -1.5 at -4.9 V with a zero crossing a -3.3 V, which indicates a favorable operation point for low chirp at -3.3 V. A chirp reduction of a factor of three between operation at -1.5 V and -3.3 V $(3V_{pp})$ is shown by calculating the EAM response to a 10-Gb/s electrical NRZ modulation.

ACKNOWLEDGMENT

The authors wish to thank J. Hanberg, GiGA—An Intel Company and P. Skovgaard, COM for providing the electroabsorption modulator.

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